FINAL REPORT

Support to X-33/Resusable Launch Vehicle technology Program

X-33 GN&C Initial Mission Success Team

Reference: Purchase order # H-29854D

Lee & Associates, LLC

December 5, 2000

1. Overview

The X-33 Guidance, Navigation, and Control (GN&C) Peer Review Team (PRT) was formed to assess the integrated X-33 vehicle GN&C system in order to identify any areas of disproportionate risk for initial flight. The eventual scope of the PRT assessment encompasses the GN&C algorithms, software, avionics, control effectors, applicable models, and testing. The initial (phase 1) focus of the PRT was on the GN&C algorithms and the Flight Control Actuation Subsystem (FCAS). The PRT held meetings during its phase 1 assessment at X-33 assembly facilities in Palmdale, California on May 17-18, 2000 and at Honeywell facilities in Tempe, Arizona on June 7, 2000. The purpose of these meetings was for the PRT members to get background briefings on the X-33 vehicle and for the PRT team to be briefed on the design basis and current status of the X-33 GN&C algorithms as well as the FCAS. The following material is covered in this PRT phase 1 final report.

- Some significant GN&C-related accomplishments by the X-33 development team are noted.
- Some topics are identified that were found during phase 1 to require fuller consideration when the PRT reconvenes in the future. Some new recommendations by the PRT to the X-33 program will likely result from a thorough assessment of these subjects.
- An initial list of recommendations from the PRT to the X-33 program is provided. These recommendations stem from topics that received adequate review by the PRT in phase 1.
- Significant technical observations by the PRT members as a result of the phase 1 meetings are detailed. (These are covered in an appendix.)

There were many X-33 development team members who contributed to the technical information used by the PRT during the phase 1 assessment, who supported presentations to the PRT, and who helped to address the many questions posed by the PRT members at and after the phase 1 meetings. In all instances the interaction between the PRT and the X-33 development team members was cordial and very professional. The members of the PRT are grateful for the time and effort applied by all of these individuals and hope that the contents of this report will help to make the X-33 program a success.

2. The Role of the X-33 GN&C PRT

The X-33 program has been pursued in a cooperative agreement between NASA and Lockheed Martin to enable flight demonstration and evaluation of technologies that may be critical to the success of next generation, reusable, possibly single-stage-to-orbit launch vehicles. The X-33 vehicle is a one-of-a-kind sub-scale prototype that will fly a series of research and technology demonstration missions in high Mach conditions that provide aero-thermal stresses comparable to a vehicle capable of reaching orbit and returning. The X-33 vehicle assembly is already in process as are preparations for initial flight test operations. A robust and risk-mitigated implementation of the vehicle's GN&C system along with its proper integration with associated vehicle subsystems will be critical to the success of the flight test program.

The X-33 GN&C system will enable fully autonomous flight, with command of the main propulsion system throttle and Thrust Vector Control (TVC), the FCAS electromechanical aerosurface actuators, as well as the Reaction Control System (RCS) thrusters to manage the mission profile. The GN&C system also interacts with all vehicle computers and avionics including the Embedded Global Positioning System (GPS)/inertial navigation system (EGI)-based navigation system. Any problems with the GN&C software, its avionics interfaces, or its functional integration with the other vehicle subsystems could have serious, adverse implications. Consequently, the X-33 GN&C and associated, interacting subsystems must be adequately validated, with identifiable issues resolved before first flight.

Development of the X-33 GN&C system, the vehicle avionics, and the other major vehicle subsystems with which GN&C interacts has been accomplished by a variety of technical groups at Lockheed Martin, NASA, Honeywell (formerly AlliedSignal), Boeing Rocketdyne, and other contractors. Each of these groups has focussed primarily on successful completion of their own subsystem development. While some integrated testing of critical subsystems has begun, much remains to be performed and screened against requirements before committing the X-33 to initial flight.

Use of the PRT to scrutinize the integrated X-33 GN&C system design, its implemented performance, and its expected operations in conjunction with other key systems can help to identify areas with disproportionate design risks. Identification of design features with disproportion risk enables those areas to subsequently receive more attention while the vehicle undergoes integration and testing. The PRT can consult with managers and technical staff from the program and can advise them regarding definition of tests that help to clarify the nature of the design capabilities and operational risks. After assessment of results from those tests, the PRT can again consult with the managers and technical staff from the program to advise them of strategies to mitigate the identified risks. For these reasons, the PRT has been formed to scrutinize the X-33 GN&C-related design status and issues.

The X-33 GN&C PRT will perform its work in two or more phases. The phase 1 assessment addressed in this report focussed primarily on vehicle GN&C algorithms and the FCAS. This phase of the PRT activity was accomplished in 7 weeks during May and June 2000. Much was accomplished by the PRT during phase 1 within the technical scope defined for that phase, but most of the follow-up interaction with the program development staff on issues identified during phase 1 was postponed until the PRT reconvenes at a later date. Consequently, the future PRT activities will involve assessment of the areas within the PRT purview that were not addressed during phase 1 as well as close-out of the issues that were identified during phase 1.

The membership of the X-33 GN&C PRT is detailed section 3. The PRT phase 1 goals and design assessment process are summarized in section 4. Section 5 provides a summary of topics and presenters at the PRT phase 1 meetings. Some significant GN&C-related accomplishments by the X-33 development team that were noted by the PRT are identified in Section 6. Some GN&C-related topics that the PRT found to require future attention as a result of limited information obtained at the phase 1 meetings are detailed in Section 7. Section 8 provides an initial list of recommendations from the PRT to the X-33 program. Appendix A provides highlights of technical observations by the PRT members that were made during the phase 1 meetings. Appendix B provides a list of acronyms used in this report along with their definitions. Note that more recommendations from the PRT to the X-33 program are likely after completion of a sufficiently thorough review of the topics detailed in Section 7.

3. The X-33 GN&C PRT Membership

Members of the X-33 GN&C PRT were selected to provide, in aggregate, the depth and breadth of expertise needed to address all the areas that will eventually be scrutinized by the PRT. Table 1 identifies these individuals.

Table 1 - PRT Membership

PRT Member	Focus Area	Affiliation

Dr. Phil Hattis	Team Lead	Draper Laboratory
Edward Bergmann	Avionics and Navigation Systems	Draper Laboratory
Frank Kirby	Propulsion	Consultant
Prof. Jason Speyer	GN&C Algorithms	University of California in Los Angeles
Don Wilkerson	Software Development Processes and Testing	Consultant
Jeffrey Zinchuk	Avionics and Fault Tolerance	Draper Laboratory

4. X-33 GN&C PRT Phase 1 Goals and Design Assessment Process

The focus of the X-33 GN&C PRT phase 1 activity was a review of GN&C algorithms and the FCAS. During phase 1, the PRT attempted to obtain sufficient insight into the GN&C algorithm and FCAS design and development status to enable identification of design implementation and development process issues that pose disproportionate risk to the success of the first X-33 flight. Based on this assessment, recommendations are made by the PRT in this report that the X-33 development team can implement to reduce the current GN&C algorithm and/or FCAS risks.

The phase 1 effort included two meetings by the PRT with X-33 managers and developers. The initial PRT meeting was held at the X-33 facilities in Palmdale, California on May 17-18, 2000. The purpose of the initial meeting was both to brief in the PRT members to the X-33 program and to provide an initial look at the X-33 GN&C algorithms' design criteria, development process, and implementation status. The second meeting was held at Honeywell facilities in Tempe, Arizona on June 7, 2000. The purpose of the second meeting was to take a look at the FCAS design criteria, implementation status, and stand-alone ground test results. Following these meetings, the PRT formulated an initial list of recommendations (see Section 8) and identified a variety of topics that the PRT deemed to require additional information and/or further assessment to attain adequate design insight which may in turn result in some additional recommendations (see Section 7).

5. Topics and Presenters at the Phase 1 PRT Meetings

Table 2 provides the subjects of all the presentations made at the May 17-18, 2000 X-33 GN&C PRT meetings in Palmdale, California along with the presenters' names and the presenters' affiliations.

Table 2 - May 2000 PRT Meeting Topics and Presenters

Subject	Presenter	Affiliation
• Introductory Briefing for the X-33 GN&C PRT	Phil Hattis	Draper Laboratory/PRT
• X-33 Program Review	Paul Landry	Lockheed Martin Palmdale
• X-33 GN&C Background	Hussein Youssef	Lockheed Martin Palmdale
• Guidance and Control Interface • Ascent Guidance	Dan Coughlin	NASA Marshall Space Flight Center (MSFC)
• Entry Guidance • X-33 Power-Pack Out Abort Trajectory Design and Performance Manager Algorithms	John Hanson	NASA MSFC

• Engine Clipping Logic	Marc Bouffard	Boeing Rocketdyne
• Ascent Flight Control	Charles Hall	NASA MSFC
• Ascent Airdata Augmentation • Reconfigurable Control	Howard Lee	Lockheed Martin Palmdale
• Transition/Entry Flight Control • Jet Selection Logic	Kerry Funston	NASA MSFC
• Terminal Area Energy Management (TAEM) Approach & Landing Guidance and Flight Control	Lee Olson	Lockheed Martin Houston
• Navigation Processing	Rich Abbott	Lockheed Martin Palmdale
• Propellant Utilization System	Barry Cantin	Lockheed Martin Michoud
• System and Software Architecture	Curtis Reichenfeld	Honeywell

Table 3 provides the subjects of all the presentations made at the June 7, 2000 X-33 GN&C PRT meetings in Tempe, Arizona along with the presenters' names and the presenters' affiliations.

Table 3 - June 2000 PRT Meeting Topics and Presenters

Subject	Presenter	Affiliation
• Introduction to FCAS • FCAS Requirement Compliance • FCAS Testing	Casey Hanlon	Honeywell
• FCAS Overview • FCAS Requirements Compliance • FCAS Testing	Jim Kern	Honeywell
• FCAS Requirements • Component Capabilities and History	Richard Larsen	Honeywell
• Dynamic Simulation and Design Analysis	Paul Evans	Honeywell
• Control Loop Design • Controller Hardware Implementation of Analytical Design • Vehicle Management Computer (VMC)-FCAS Controller Latency • FCAS Software	Ed Johnson	Honeywell

6. Some Significant X-33 Program GN&C-Related Accomplishments

The goals of the PRT were to identify aspects of the design of X-33 GN&C-related subsystems that had disproportionate risk and to make recommendations regarding how to mitigate that risk. However, in the course of doing its phase 1 assessment, the PRT also developed some very favorable impressions. The following subsections identify PRT observations about the high quality of X-33 development team members and some of the significant GN&C-related development accomplishments to date on the program. Quality of Development Team PersonnelThe technical caliber and level of expertise of individual GN&C-related subsystem developers was very high.

6.1.1 The degree of individual cooperation among the X-33 program developers was excellent. They had a strong spirit of teamwork and commitment to the program.

6.1.2 The level of algorithm and software design aptitude prevalent among the development staff is more than adequate to meet the X-33 vehicle GN&C-related application challenges.

6.1.3 At this stage of the program, despite recent reductions in the program's level of effort, the amount of informal technical communication flow among individual team members involved in GN&C algorithm and FCAS development is quite good.

6.2 Quality and Quantity of Work Accomplished

6.2.1 The design of this complex vehicle was done with the cooperation of many companies in a very short time. In order to accomplish this task, many of the subsystem designs had to rely on internal information and redundancy to achieve the failure tolerance, performance, and reliability goals. This was accomplished by each of the subsystem teams with which the PRT interacted. Although this design approach may have added to the vehicle weight and power consumption, it substantially reduced the level of effort required for the software development, integration, and validation. It was the best approach for this X-vehicle design

6.2.2 The current GN&C-related avionics architecture and design generally seem sound and conservative. The avionics development is nearly complete, and most of the hardware is ready for use in the final vehicle assembly.

6.2.3 The GN&C algorithm and software architecture also seems generally sound and conservative. There is a nearly complete implementation of flight code with much of the developmental testing at the software component level already complete.

6.2.4 The FCAS development team has produced a complete, self-sufficient subsystem design and has done testing with power sources similar to what will be on the X-33. This development effort seems to have proceeded very well. The actuators appear to be nearly ready for flight.

6.3 Some Other GN&C-Related Accomplishments

6.3.1 The program implemented GN&C-related Interface Control Documents (ICDs) very early and used this mechanism to define, track, and manage the interfaces, implementation, and derived requirements for each of the subsystems.

6.3.2 The program had a Configuration Control Board (CCB) in place early that handled many of the GN&C-related system issues. This CCB reviewed proposed changes and tracked the impact of approved changes.

6.3.3 The program has applied a requirements management tool, the Dynamic Object Oriented Requirements System (DOORS), that facilitates GN&C-related requirements traceability.

7. Some GN&C-Related Topics Requiring Further Attention

During the phase 1 PRT efforts, some topics were identified that required additional information to enable completion of a satisfactory assessment, but that information could not be obtained within the phase 1 period of performance to enable close out of the topics. These topics are identified in Section 7.1. Also, the PRT identified other topics that require attention but which were outside of the phase 1 review scope. These topics are identified in Section 7.2. All the topics in Sections 7.1 and 7.2 should be addressed before the PRT completes its full review of the integrated X-33 GN&C system and are listed here to assure that they are known and properly addressed when the PRT reconvenes. Note, however, the topics listed in this section do not necessarily constitute a comprehensive list of areas that must be addressed by the PRT to complete its intended integrated GN&C system review scope. Also, no priority is implied by the order in which the topics are listed.

It is important that the X-33 program developers and managers understand that recommendations by the PRT to the X-33 program that are not already provided in Section 8 may result following assessment of the areas identified in this section.

7.1 Topics Within the PRT Phase 1 Scope that Require Further Scrutiny

7.1.1 GN&C Algorithm Requirements

7.1.1.1 Ambiguous or Vague Requirements. The PRT found some of the GN&C algorithm design requirements to be ambiguous or vague, complicating algorithm testing and creating a risk of design misunderstandings across the X-33 development team. Any program plans to identify and definitize ambiguous or vague requirements should be reviewed for completeness. A trace of the GN&C algorithm requirements to the subsystem features that implemented the requirements and identification of the processes intended to validate the requirements would be of interest to the PRT to help to address this issue. The same information may also be an effective tool for developers to isolate the requirements that remain ambiguous or vague.

7.1.1.2 Power-Related FCAS Controller Design Constraints. Review is needed of the specific power system constraints that motivated flow-down or associated developer-derived FCAS controller design requirements. The PRT noted that Honeywell had applied low voltage operation derived requirements to the FCAS based on technical issues raised by other vehicle development team members that are not formally documented by the program. This made it apparent that the completeness of the documentation of the power system-derived design constraints and the origin and rationale of those constraints needs review. An assessment is also needed of plans to test the flowed-down and developer-derived requirements resulting from the power system constraints.

7.1.1.3 Failure Tolerance Requirements. The vehicle tolerance requirements for GN&C-related subsystem failures should be reviewed along with the criteria for selecting these requirements. This issue results from PRT observation that a variety of different redundancy strategies are used on the vehicle GN&C-related subsystems (e.g., fully redundant FCAS motor controllers vs. use of RCS thruster authority overlap for functional redundancy). The actual failure tolerance requirements and the intent of those requirements must be fully understood prior to determining whether each of the GN&C-related subsystems actually meets those requirements.

7.1.2 GN&C Algorithm Design

7.1.2.1 Flight Phase Sequencer. Additional details are needed of the flight phase sequencer logic to enable addressing how it handles reconfiguration requirements and how it accommodates aborts.

7.1.2.2 GN&C Features to Accommodate Main Engine and TVC/Thrust Lever Control (TLC) Dynamics. A review is needed of the GN&C algorithm features that are included to accommodate the ascent main engine and TVC/TLC dynamics under nominal, dispersed, and Power Pack Out (PPO) flight conditions. Control law treatment of any significant nonlinear engine and TVC/TLC effects and associated analysis of expected closed-loop response should be part of the review.

7.1.2.3 RCS Thruster Selection Criteria. The briefings to the PRT indicated that the entry RCS thruster selection is based on flight-specific thruster selection tables. The basis for generating the tabulated thruster selections and for determining the robustness of the control system response resulting from the flight-specific tabulated selections should be scrutinized.

7.1.2.4 First-Flight, Non-Intended Code Paths. The GN&C algorithm briefings to the PRT during phase 1 indicated that the first X-33 flight will have algorithm features in the flight software load that are not expected to be used. The PRT is seeking clarification of how testing will verify that non-intended code paths are avoided in the initial flight. Also, clarification is sought regarding how integrated testing plans will focus on the required first flight capability.

7.1.2.5 Ascent Lift Management. Use of vehicle lift during ascent can affect guidance. Clarification is sought about how vehicle lift is managed and/or applied during ascent.

7.1.2.6 Mission Manager Role with the Performance Manager. Because the performance manager operates in the mission manager processor, an assessment of the mission manager and how it executes the performance manager is needed, including mission manager processing throughput and timing considerations when the performance manager is active.

7.1.2.7 Landing Gear Braking. Insight is needed regarding whether main landing gear braking is disabled until after nose gear touchdown is confirmed.

7.1.2.8 PPO-Induced Guidance I-loads. Clarification is sought regarding whether PPO-induced guidance update I-loads define a new reference trajectory or reference vehicle attitude history.

7.1.2.9 Control Effector Mixing and Stability. The FCAS effectors are blended with the TVC/TLC system during ascent and with the RCS thrusters during entry to achieve vehicle control. A review is needed of how the control laws accommodate the dissimilar character of the effectors and how stable interaction of the effectors is assured during nominal, dispersed, and anomalous flight conditions.

7.1.3 GN&C Algorithm-Derived Flight Software

7.1.3.1 I-Load Validation Plan. Details are needed regarding how I-loads will be validated and how I-loads will be re-validated after changes are made. Also, responsibility assignments should be identified regarding formulation of I-load test criteria and definition of integrated tests (with dispersions and faults) to verify I-loads.

7.1.3.2 Basis for the Ascent Mixing Gains. A review is needed of ascent mixing gain selection criteria (This assessment activity should be done subsequent to the review discussed in item 7.1.2.9).

7.1.3.3 Software Responsibilities. Program responsibility assignments for evaluating and testing the GN&C response under the range of possible control effector failure conditions and the applicable test plans need to be reviewed to verify comprehensive coverage. (This issue arose when it became apparent that failed aerosurface scenarios are not being evaluated by developers of the entry control algorithm.)

7.1.4 GN&C Algorithm Performance

7.1.4.1 GN&C Robustness with Faults. An overview is sought that addresses GN&C fault tolerance and GN&C robustness in the presence of vehicle faults. As part of this action item, faults to which the GN&C system is required to be tolerant should be identified. Flush-mounted Air Data Sensors (FADS) Dynamic Pressure and Airspeed

Measurement Accuracy. The expected accuracy of the FADS-derived free-stream-relative dynamic pressure and airspeed measurements on the initial X-33 flight should be addressed along with the impact of the expected uncertainties in these air-relative state measurements on the performance of the TAEM Guidance and Control (G&C) loop.

7.1.4.2 Center of Mass (CM) Measurement Accuracy. The accuracy of the CM estimation by the Vehicle Propellant Manager (VPM) and the impact of resulting uncertainty on the accuracy of the EGI-derived navigation states should be reviewed.

7.1.4.3 Accuracy of Navigation States Derived Outside the EGI. A summary is needed of the navigation states that are generated by the EGI but are also derived outside the EGI because they are not output from the EGI to the Flight Manager (FM). The resulting differences in the accuracy between the EGI-derived and FM derived versions of these states should be assessed along with the impact on G&C performance of any loss of accuracy of the FM version of these states.

7.1.4.4 Effect of PPO-Related Reconfiguration Delays. An assessment is needed of the consequences of the PPO-related reconfiguration delays on vehicle response in negative post-PPO control regimes. Assurance is needed that no catastrophic vehicle flight path divergence can result.

7.1.5 FCAS

7.1.5.1 Pneumatic Load Assist Device (PLAD) Current Averaging. The suitability and correctness of the current "averaging" scheme used to activate the PLAD needs to be addressed.

7.1.5.2 Open-Failed PLAD Valve Likelihood and Consequences. Information is needed regarding the likelihood of an open-failed PLAD vent valve.

7.1.5.3 FCAS Effector Failure Response Lag Effects. The effects of the latency in FCAS effector failure detection and reconfigured backup channel initial response need to be addressed under worst case aerosurface failure conditions (with worst case determined by greatest potential for inducing vehicle flight divergence). Account should be made for the detectability and response lags associated with intermittent as well as hard failures.

7.1.5.4 Load Effects on Electromechanical Actuator (EMA) Frequency Response. The effects of loads on the EMA frequency response and the impact of any response changes on control loop stability need to be screened, including how these effects (if significant) have been factored into the FCAS design.

7.1.5.5 EMA Duty Cycle Demands and Capabilities. A summary is needed of how the maximum expected in-flight duty cycle rates of the EMAs relate to the EMA operational capabilities.

7.1.5.6 Dual PLAD Operation Effects. All ground tests of the PLAD that were addressed in the June 2000 PRT meeting involved a single system. A review is needed of any analysis that indicates what changes in PLAD response will result from feeding two flight PLADs off the single pressurized gas supply.

7.1.5.7 Reduced Voltage Response. A review is needed of the expected FCAS control loop response when the low voltage operational mode is invoked.

7.1.5.8 Planned FCAS Failure Scenarios for Closed-Loop Tests. The scope of FCAS failure test cases to be run in combination with the closed-loop GN&C system needs to be summarized and reviewed to assure that plausible high-stress cases are covered.

7.1.5.9 Common Mode Failure Scenarios. Insight is needed regarding what sources of common mode failures may exist for the FCAS primary and secondary actuator channels along with their likelihood.

7.1.5.10 Command/Actuator Spectral Response. FCAS hardware-in-the-loop (HWIL) test data presented to the PRT at the June 2000 meeting showed some spectral characteristics that warranted further scrutiny. Results of any spectral analysis of the FCAS command/actuator loop response and the explanations for resonance and or "beating" phenomena identified in the spectral response should be reviewed.

7.1.5.11 FCAS EMA Dispersion Characteristics and Response. An assessment is needed of the basis for determining the expected FCAS EMA dispersions and the expected control response and stability margin effects due to those dispersions. A basis for constructing appropriate worst case stress tests should be addressed that does not put undue reliance on Monte Carlo testing. Included should be consideration of at least uncertainty in control effectiveness, EMA duty cycle effects, and power drain effects.

7.1.5.12 Rate and Current Limit Change Safeguards. A feature exists to enable down load changes to the FCAS rate and current limits. A review is needed of how these limits are assigned and verified before first flight, as well as how the values in the software are safeguarded from in-VMC change during flight.

7.2 Topics Outside the PRT Phase 1 Scope that Warrant Scrutiny

7.2.1 GN&C Operations

7.2.1.1 Ground Intervention Strategy and Procedures. Scrutiny is needed of the criteria for ground intervention into GN&C during pre-launch and flight as well as the procedures for determining and accomplishing the ground intervention. Also, the information available to ground control personnel for making GN&C-related intervention decisions and the basis for assuring that the ground control personnel adequately understand that information should be reviewed.

7.2.1.2 Launch Restrictions. A listing is needed of GN&C-related launch restrictions to support a review of them.

7.2.1.3 GN&C Initialization. A review is needed of how GN&C initialization prior to launch will be accomplished and verified.

7.2.1.4 Pre-Flight Checkout. A review is needed of the scope and nature of GN&C-related subsystem pre-flight checkout that will be performed prior to first flight.

7.2.1.5 Abort and Flight Termination Criteria. An assessment is needed of the criteria used in software and at the ground operations facility for determining that an abort is appropriate and/or flight termination is necessary. Applicable on-board and ground response procedures also warrant scrutiny.

7.2.1.6 Post-Landing GN&C-Related Functions. A review is needed of the GN&C-related system operations that are required after landing, including the ground system linkages that are needed to enable those operations. Also, any on-board power requirements associated with post-landing GN&C-related operations should be addressed.

7.2.1.7 Initial Flight Certification. The process for certifying the GN&C-related systems are ready for flight should be screened including a review of how pre-flight testing results are factored into the certification process.

7.2.2 Avionics

7.2.2.1 Power Requirements Analysis. A review is needed of the basis for sizing batteries and establishing their discharge requirements to assure that the GN&C avionics and associated control effector in-flight power needs are met. Nominal and peak current drain should be addressed as well as the allowable voltage fluctuations, expected depth of battery discharge, strategies for short-circuit protection, and charging/monitoring requirements.

7.2.2.2 1553 Signal Traffic. An assessment is needed of the GN&C-related 1553 bus signal traffic for a nominal X-33 mission. This should include the list of 1553 data words to/from the bus remote terminals.

7.2.2.3 Navigation Simulations. A review is needed of the implementation and results of the simulations involving the EGI and the use of differential GPS data. The EGI change history and current design verification process should be addressed. The means by which differential GPS is applied, the magnitude of differential GPS data update delays, the means by which differential GPS data update delays are accommodated, and how resulting navigation dispersions affect guidance should all be covered. The analysis and testing used to verify the GPS antenna coverage, satellite tracking, and satellite switching for scenarios applicable to the first X-33 flight should be included. Any identified issues or launch restrictions associated with limitations on satellite visibility by the antenna should also be covered.

7.2.2.4 Processor Throughput. A review is needed of the predicted and measured throughput as well as memory loading of flight processors used by GN&C-related functions. This should cover flight manager/mission manager processors (in the vehicle management computers), data interface units, and engine manager (engine controller) processors.

7.2.2.5 Environment Susceptibility. An assessment is needed of any analysis performed by the X-33 development team regarding the environment exposure envelope for all critical avionics packages and the susceptibility of each class of avionics box to adverse effects due to the environment. This should cover avionics directly related to GN&C data processing as well as controllers for the main engines and the FCAS actuators.

7.2.2.6 Grounding Strategy, Static Discharge Consequences, and Electromagnetic Interference (EMI) Effects. The effectiveness of the vehicle's electrical grounding strategy, the potential for static discharge, and the possible effects of static discharge on the avionics should be reviewed. Also, the level of vehicle screening for EMI sources and the degree of avionics protection from EMI effects should be addressed.

7.2.2.7 Component Fault Detection Process. An assessment is needed of the algorithmic criteria for identification of GN&C-related avionics component faults. This should include strategies to detect intermittent failures as well as "steady" (continuously observable) failures.

7.2.2.8 HWIL Stress Tests. Plans for GN&C-related subsystem HWIL stress tests need to be reviewed. This review should address at least the following areas:

- The subsystem and associated Integrated Test Facility (ITF) test procedures, providing information necessary to determine what has not been verified at the subsystem level and what must be verified at the ITF HWIL level.
- Identification of the most stressful test cases that result from plausible dispersion and or failure effects. Definition of these cases should include consideration of the effects of partial power system failures and/or 1553 bus anomalies.

7.2.3 Propulsion

7.2.3.1 Main Engine Models and Dynamics including TVC, TLC, and PPO. The GN&C system must accommodate the main engine thrust dynamics including PPO scenarios for which there are a variety of special GN&C algorithm features. The following items need to be reviewed to be sure they are properly accommodated in the GN&C algorithms:

- Main engine thrust vs. time during throttle up or down from an operating point.
- Main engine thrust vs. time for nominal operations and PPO engine shutdown (including shutdown thrust vs. time as a function of engine power level prior to shutdown).
- The ascent main engine interaction with the airflow around the vehicle with respect to its effect on the vehicle's aerodynamics. A review of the engine/aerodynamics interaction model is needed that addresses the effect of the engine plume on aerodynamics as a function of atmospheric condition, flight state, throttle setting, and TVC/TLC usage including uncertainty effects. If the aerodynamic effect of the engine plume is sensitive to aerosurface positions, then the nature of those effects should also be covered.
- The models and model uncertainties of the expected torque resulting from TVC and TLC under nominal and PPO flight conditions. Included should be information about how the models and uncertainties change as a function of vehicle Mach number, dynamic pressure (Q), angle of attack (α), and side slip (β).
- Main engine operating conditions and propellant flow rates for nominal and PPO scenarios as a function of throttle and TVC/TLC settings (including variations between left and right engine response for nominal flight due to TVC/TLC).
- PPO response event sequence and timeline, the models of these events, the expected quality of these models, as well as the implication of PPO on vehicle dynamics (including possible transient disturbance rates on the vehicle).
- The process for validating the accuracy of the propulsion dynamics models including TVC/TLC effects.

7.2.3.2 RCS Performance and Reconfiguration. There are many aspects of vehicle flight control that depend on detailed knowledge of the RCS system response characteristics. Assessment is needed of the following items to assure that they have been properly accommodated:

- The expected RCS on/off response times, latencies, and impulse characteristics.
- Sources and magnitudes of jet thrust variations.
- Operation/interaction with the jet exciter.
- Failure modes, failure detection strategies, as well as failure override logic including the override logic interaction with the Vehicle Subsystem Manager (VSM).
- The status and resolution plan of the currently unsatisfied requirement to be able to fire five RCS jets simultaneously.

7.2.3.3 Engine and TVC/TLC error effects. A review is needed of the TVC/TLC models, their uncertainties, and the effects of those errors on GN&C including a discussion of the GN&C robustness provided to accommodate those errors.

7.2.3.4 Main Engine Control. Scrutiny is needed of the control algorithms, Redundancy Management (RM), and associated command latency (under nominal and fault conditions) for the main engines. Included should be information regarding what computers manage PPO execution, associated valve control/reconfiguration, and

TVC/TLC valve management. The review should also cover how the design blocks any path by which main engine propellant crossfeed valves can be improperly configured without an actual PPO.

7.2.3.5 Propellant Depletion Detection. A review is needed of the main engine propellant depletion detection strategy, the depletion detection cross check, as well as the associated RM strategy. Also the criteria for selecting the location of the liquid oxygen depletion sensor package including the role that the propulsion contractor had in placing that sensor package should be covered.

7.2.3.6 PPO Thrust Imbalance. The magnitude of engine thrust imbalance due to asymmetric gas generator flow under PPO flight conditions should be assessed and the status of models of this effect in the simulations should be addressed.

7.2.3.7 TVC/TLC Limits. A review is needed of whether there are any time limits for holding the TVC/TLC at or near +/-15%, or any other engine constraint-related restrictions on the TVC/TLC usage. Treatment of any such constraints in the GN&C algorithms should also be covered.

7.2.3.8 Pressure Sensor Failure Modes. Possible failure modes of the propellant utilization pressure sensor(s), and their likelihood, should be reviewed.

7.2.4 GN&C-Related Software and Associated Testing

7.2.4.1 End-to-End Flight Test Plan. An assessment is needed of the X-33 program's end-to-end-flight GN&C testing plans and the means by which those plans will be accomplished. This should encompass nominal, dispersion, and inserted-fault tests. There should be consideration of the means by which the envelope of vehicle capability will be determined. Also, plans should be addressed regarding intended flight-test signature simulations against which actual flight test results can be compared.

7.2.4.2 GN&C-Related RM. A review is needed of the GN&C-related RM requirements and implementation to assure adequacy and uniformity of RM across the GN&C-related subsystems. This should cover at least the following areas:

- Guidelines on how to detect and handle failures for each GN&C-related subsystem.
- The fault handling logic for each GN&C-related subsystem.
- Methods for handling both hard and intermittent failures.
- Strategies for differentiating between actual subsystem failures and sensor failures.
- How subsystem Built in Test (BIT) data is applied.

7.2.4.3 Software Development/Testing Processes and Exception Handling. A review is needed of the GN&C flight software development and testing processes and the exception handling to be applied in the flight processors executing GN&C-related software.

7.2.4.4 Stability and Dispersion Analysis. The GN&C algorithm developers that briefed the PRT indicated that much work remains to be done on GN&C stability and dispersion analysis. When this work is more complete, there should be a review that addresses the process and results of GN&C stability and dispersion analysis for each flight phase including account for how significant nonlinear effects have been treated. The use of frequency domain and time domain analysis should be addressed as well as how the results of these two analysis strategies are compared. The applicability of any stability analysis that preceded completion of the final design versions of the algorithms should also be addressed. Of particular interest are measures of remaining margins under stress test cases. Also of special interest is the response of the vehicle under dispersed conditions in PPO-flight-induced negative control regions (to assure there is no catastrophic flight path divergence).

7.2.4.5 Software Development Metrics Review. Metrics of GN&C software development and associated error rates need to be reviewed to assess the health of the software development process and the software integration process. Included in the metrics should be the number and types of errors found in each phase of the development and testing as well as a categorization of errors by major cause (e.g., requirements misunderstanding, design error caused by [*reason*], coding error, test data error, etc.).

7.2.4.6 Implemented VMC Software Responsibility. In the May 2000 PRT meeting it became apparent that at least two different companies have been generating software to execute on processors sharing the same back plane within the VMC. A review of the final division of the associated software development and the assigned testing responsibility is needed as well as a discussion of how compatibility of all resulting object code has been assured.

7.2.4.7 Software Maintenance. A review is needed of the processes applied to establish controlled records of the GN&C software design criteria and to assure maintainability of the GN&C software as well its development and test environment throughout the vehicle design, development, and initial flight test operations. This should include discussion of the GN&C software configuration management plan and implementation.

7.2.4.8 Integrated Test Plans. A review is needed of the status of the GN&C integration test plan and intentions regarding formalization and standardization of the applicable suite of test cases.

7.2.4.9 Navigation Data Source Selection. An assessment is needed of any possible adverse consequences of each VMC doing its own navigation package data source selection. Relevant information includes:

- Values, limits, and thresholds used on navigation package pair-wise comparisons.
- The expected trends in output navigation state deviations between VMCs if not all VMCs are able to read all navigation packages.
- The basis for VMC comparison of output navigation state data.

7.2.4.10 Voted VMC Data. VMC cross channel data link voted variables should be scrutinized. Both the data words that are voted and the associated thresholds used to detect failures should be addressed.

7.2.4.11 Software parameter Input Management. A review is needed of the process for managing assignment of flight software parameters before and during an X-33 flight. This should address the means for verifying the parameter default load, the process for updating the flight parameters, and the means applied to control access to the on-board flight parameter data.

7.2.4.12 ITF Use to Verify FCAS. A review is needed of how the ITF will be used to verify FCAS load predictions, control margins, and expected PLAD gas usage.

7.2.5 General Model and GN&C-Related Subjects

7.2.5.1 Requirements Traceability and Verification. How the X-33 program will assure GN&C-related design requirements traceability to all applicable system and subsystem levels and will systematically verify those requirements should be addressed.

7.2.5.2 Tracking of Derived Requirements. Many derived requirements have been applied in the development of GN&C-related subsystems to assure acceptable performance and to follow sound engineering practices. A review is needed of the process by which these derived requirements are documented and tracked from the subsystem development level to the integrated-GN&C system and vehicle level.

7.2.5.3 Listing and Status of Models Used in GN&C-Related Simulations. A list of environment, vehicle dynamics, and component performance and response models used in major GN&C development simulations and the ITF should be generated for review. The list should also address the sources of the models and the means of validation of the models. This will enable an assessment of the adequacy of the models used for design development and testing as well as the completeness of modeled features.

7.2.5.4 GN&C Development Records. A list of any documentation that provides a record of the GN&C development status, associated reviews, identified issues, and resulting change history should be prepared to facilitate identification of items warranting scrutiny.

7.2.5.5 GN&C-Related Documentation Tree. A listing of X-33 GN&C-related documentation tree is needed. This should cover applicable GN&C-related subsystem hardware and software documentation. In the case of the software it should be from the Software Development Plan (SDP) level down.

7.2.5.6 Applicable SDPs. Material reviewed by the PRT seemed to indicate that there are two SDPs associated with GN&C-related system development (documents 604D003 and 604D0029). Clarification is needed on the role of each of these documents, and their precedence if there is any technical overlap.

7.2.5.7 Touchdown Detection. Relevant design information is needed to assess what is done to make vehicle touchdown and nose-down detection reliable.

7.2.5.8 Failure Management and Effects Analysis (FMEA). An assessment is needed of the X-33 program plan for FMEA, the status of that work, and significant FMEA-related conclusions that have been made. Special attention should be provided to FMEA results for components whose failures can affect multiple components of other subsystems (e.g., power system component failure effects on the FCAS).

7.2.5.9 Landing Gear Lateral Loads. An assessment is needed of what has been done to evaluate and determine the acceptability of lateral loads on the landing gear under cross wind conditions.

7.2.5.10 First Flight System Capabilities, Expectations, and Margins. To help the PRT evaluate validation and verification plans prior to first flight, a review is needed of the expected vehicle GN&C-related capabilities, those capabilities that will be exercised on the first flight, and the applicable design margins.

7.2.5.11 Design to Reliability Requirements. The apportionment of reliability requirements to subsystems and the plans to test satisfaction of the apportioned requirements should be scrutinized to assure that the integrated vehicle will meet overall system reliability requirements.

7.2.5.12 Tracking of Reliability and Limits Issues. A review is needed of the process with which component/subsystem reliability and operational limits issues that are identified by subsystem developers are tracked throughout the vehicle development program.

7.2.5.13 Performance Testing Methods. An assessment is needed of the vehicle performance characteristics that can be evaluated on the ground before the initial flight vs. performance characteristics that must be evaluated during flight.

8. Initial PRT Recommendations to the X-33 Program

The following items are the initial recommendations from the PRT to the X-33 program that address areas in which the PRT obtained enough information during phase 1 to draw specific conclusions. Eventually more PRT recommendations regarding the X-33 development process and design are likely since during phase 1 of the PRT assessment there was insufficient information in some areas to draw specific conclusions and some other areas of concern to the PRT were not addressed at all. There is no priority associated with the order of this recommendation list.

8.1 GN&C Algorithm Requirements Definition and Design Implementation

8.1.1 Clarifying Ambiguous or Vague Requirements. All system and subsystem level specifications should be scrutinized for ambiguous or vague requirements. Clarification of those requirements should be provided to assure that they are testable.

8.1.2 VPM Adequacy. The suitability of the adaptation of the VPM from an expendable, cylindrical rocket stage propellant management system to a VPM on a reusable vehicle with complex tank geometry needs to be carefully scrutinized given the criticality of X-33 propellant depletion during ascent to successful vehicle return. Also, the RM strategy needs to be reevaluated to assure that its failure detection coverage is sufficient.

8.2 Documentation and Knowledge Capture

8.2.1 Design and Implementation Knowledge Capture. Given the possibility of a hiatus in the GN&C software development cycle, and the possible loss of many key developers before the work resumes, the program must develop a plan to capture critical design criteria and implementation strategy information.

8.2.2 Developer-Derived Requirements Capture. All requirements applied during algorithm development should be captured in testing whether they are flowed down from the higher-level program requirements or are developer derived. Developer-derived requirements should also be consistently documented including motivation for their inclusion. In any instance that derived requirements within a subsystem could impact design requirements in other vehicle subsystems, they should be flowed up to the vehicle requirements level and flowed back down to the other affected subsystems. A program-wide requirements management process update seems necessary to assure consistent and proper treatment of all developer-derived design requirements.

8.2.3 Consistent Technical Information Record Keeping. The vehicle integration contractor should consistently apply configuration management/record keeping to critical technical information in the X-33 program. At least the following areas should be covered:

- Downward-flowed requirements (which the program already properly addresses).
- Upward-flowed GN&C design criteria and requirements that have been or should be exchanged between program contractors and development teams.
- Subsystem contractor critical development and design documentation.
- Deliverable software configurations.
- Supporting development and test tools.
- Final test data and test results.

8.2.4 Subsystem Documentation. The program should assure archival control and future access to all subsystem design and development documentation.

8.3 GN&C-Related Software and Models

8.3.1 Software Maintainability. The program should address the maintainability of the simulation and flight software development environment, source code languages, as well as the source code. Contributing factors to concerns in this area are the variety of participating contractors, differences in algorithm and software development methodologies employed across contractors, limited documentation in some areas, and turnover in staff as the program goes through a reduced level-of-effort phase. A plan should be put in place to assure that all critical software components (in flight code, development, and testing tools) are sufficiently well documented to enable development work to continue even if any key individual developer becomes unavailable to the X-33 program. Attention should also be given to the viability of continued use of Fortran development tools.

8.3.2 Model and Software Verification. All simulation model and utility software should be verified without reliance on use of flight software components.

8.3.3 Algorithm Peer Reviews. The X-33 program should assure completion of peer reviews of all GN&C-related algorithm designs before the final flight code implementation is completed. It would have been best if the peer review process had been accomplished prior to initial delivery of the algorithms to coders. However, up to now the peer review process has not been applied consistently by all the subsystem developers. This increases the demand for error detection during testing, implies a longer integration testing cycle, and increases the probability of errors in the delivered flight software. To limit these issues and risks, the program needs to establish a review process that verifies that the design intent for all algorithms was properly formulated and correctly transmitted to as well as understood by flight code developers in cases where peer reviews were not already done. A process must also be put in place to enable revision of the algorithms and resulting flight code when new peer reviews find design intent errors.

8.3.4 C++ Language Implementation Ambiguities. The C++ language that is being used for part of the X-33 GN&C-related software development has a degree of ambiguity that requires extensive user experience to fully anticipate. Subtle source code language usage changes can significantly alter object code response. The development team should be cognizant of the impacts of that ambiguity which may not become fully apparent until integrated flight software testing is underway. Adequate time and resources should be provided to support associated implementation problem resolution when integration and checkout of the software developed in the C++ language with the rest of the flight software is accomplished.

8.3.5 Lead Software Engineer. Because the software work related to the X-33 GN&C involves numerous organizations and poses many integration challenges, the X-33 program should consider having a lead engineer dedicated *exclusively* to addressing top-level GN&C software issues across all GN&C-related subsystems. This person would be the focal point for overseeing the coordination of all the applicable software design, integration, testing, delivery, and sustaining engineering functions. The role of this individual would be to provide a clear path of technical responsibility for the overall implementation and function of the vehicle software, but this individual's activity would be in coordination with the continued work performed by lead software engineers within the development organization of each subsystem.

8.4 GN&C-Related Analysis and Testing

8.4.1 GN&C Algorithm and FCAS Stress Test Cases. The X-33 program should come up with means to define priority GN&C algorithm and FCAS stress test cases in order to understand GN&C stability properties without excessive reliance on extremely numerous Monte-Carlo tests. Also consistent approaches to GN&C algorithm and FCAS stability assessment should be formulated and uniformly applied throughout the development process. Consistent approaches to stability analysis are necessary to avoid stability screening lapses when developers of specific algorithms or FCAS control features change and/or when knowledge of specific algorithm or FCAS design criteria is lost during program extensions (despite best efforts to retain that knowledge).

8.4.2 GN&C Test Suite Definition. The test suite for GN&C algorithms and associated software needs complete definition and should be kept under configuration control.

8.4.3 Performance Manager Testing. The complexity, processing burden, and non-deterministic nature of the performance manager poses unique challenges in assuring robustness and sufficiently comprehensive testing. Special attention should be provided to addressing these performance manager issues, and careful review of the testing process and results should be assured. If use of the performance manager is not intended during the first flight, then it will be necessary to verify that the performance manager can not inadvertently impact the first-flight GN&C operations and performance.

8.4.4 TVC/TLC Effects on PLAD Gas Usage. Because the FCAS is blended with the main engine TVC and TLC for ascent control, the effects on PLAD gas usage due to uncertainties in the TVC and TLC responses must be assessed. Failure to properly screen for these coupled system effects risks depletion of the PLAD gas supply during flight.

8.4.5 Full-Up FCAS/Vehicle Testing. Full-up testing that addresses the real response and performance margins of the FCAS and PLAD systems within the complete GN&C (avionics and software) system and overall vehicle is needed to help validate the system's response and readiness for first flight. This may be best accomplished by using the actual flight vehicle as the "simulation" test platform. Tests should encompass FCAS failure detection and reconfiguration scenarios that are managed by software in the VMC.

8.4.6 Flight Phase Change Response. A systematic evaluation should be performed of the acceptability of the GN&C response when the algorithms switch between flight phases. The flight phase switching response should be assessed for performance acceptability under nominal, dispersed, and most likely anomalous flight conditions. ITF test plans should explicitly address these algorithm evaluation requirements.